Effect of Process Parameters on Surface Roughness of EN-19 Steel Investment Casting

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Abstract— The present study is concerned with the investigation of surface roughness of EN-19 steel castings. The castings were produced by investment casting process with a wall thickness of 4 mm. Experiments were conducted as per Taguchi's L9 orthogonal array. Castings were made under the constraint of different process parameters like mold pre-heating temperature, pouring temperature, number of coats and type of sand with different grain fineness numbers to investigate their effects on the surface roughness of the final castings. The results revealed that the more number of coats significantly reduces the hardness of final castings. The surface roughness of EN19 steel increases with mold pre-heating temperature, pouring temperature whereas, better surface finish was obtained when zircon sand is used.

Keywords: Investment Casting, Hardness, Taguchi, Pouring Temperature, Surface Roughness, Pre-Heating Temperature, Sand Type

I. INTRODUCTION

The investment Casting is a highly specialized method to produce near net shape. It has got several advantages over other casting processes like smooth and pleasing finish, reduced machining allowances, close tolerances, flexibility of alloy selection. Investment casting is known for its quality castings rendering good quality, surface finish, and other desirable mechanical properties. Now a day's fuel efficiency requirement for cars and trucks has led to the increased use of low density materials such as aluminum. However, these materials, which require tremendous amounts of energy for their production, have significant drawbacks with respect to strength and cost. Lightweight iron and steel casting designs have been largely ignored despite their obvious cost and property advantages. It also clearly offsets the weight benefit of aluminum alloys when the weight and cost per unit of yield strength is considered. Thus thin wall castings are taken for current study. Investment casting is a cheaper alternative than forging and machining since waste material is kept to a minimum. The investment casting process has increasingly been used to produce components for the automobile and aerospace industry. The surface roughness of the product must be minimum or negligible to improve performance of castings.

The surface roughness can significantly reduce the fatigue strength of steel castings, however better surface finish would reduce the size of large undercuts with increase in resistance to crack initiation and hence improve fatigue life.

A. Process Parameters

In order to identify the process parameters which are going to affect the quality of the casting produced by investment casting process, an 'Ishikawa cause effect diagram' was constructed, as shown in Fig.1.

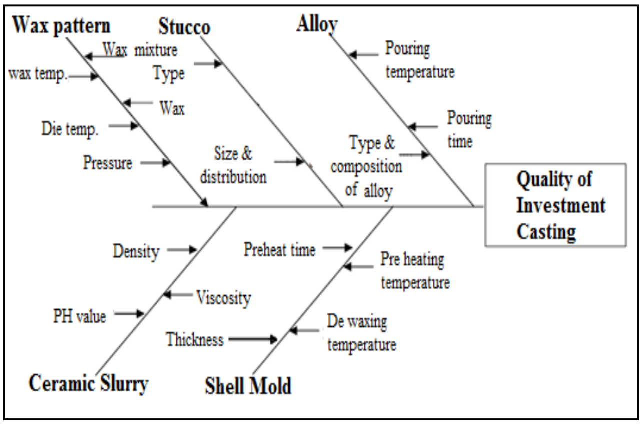

Fig. 1: Process parameters affecting Investment Casting process

The process parameters based on wax pattern, shell mold and pouring metal which may affect the surface roughness of the casting will be listed as below.

1) Wax pattern related parameters: wax composition, viscosity of wax and shrinkage characteristic of wax and injection parameters such as temperature, injection pressure, and injection temperature and dwell time.
2) Shell mold related parameters: slurry composition, coating thickness, stucco size, dewaxing temperature of mold and mold pre-heating temperature.
3) Pouring related parameters: pouring temperature, pouring time, composition of alloy.

The mold is pre-heated to a specific temperature and filled with molten metal. It is done to remove any residues of wax and harden the binder. The pour in the pre-heated mold also ensures that the mold will fill completely. Ceramic shell materials are fired to remove moisture (free and chemically combined), to burn off residual pattern material and any organics used in the shell slurry, to sinter the ceramic, and to pre-heat the mold to the temperature required for casting. The pouring temperature will have direct influence on the hardness of casting. Generally, for coating on wax pattern, silica, zircon, alumina and various aluminum silicates are commonly used as refractory for both slurry and stucco in making ceramic shell molds. Alumina being expensive is only used selectively in directional solidification processes. Other refractories, such as graphite, zirconia and Yttria have been used with reactive alloys. Yttria is used in prime coats for casting of titanium alloys.

II. EXPERIMENTAL WORK

Taguchi recommends Orthogonal Array (OA) for design of experiments. OA's are generalized Greco-Latin squares. The design of experiment is to select the most suitable OA and to assign the parameters and interactions of interest to the appropriate columns. The selection of a particular orthogonal array is based on the number of levels of various factors.

Here, to conduct the experiments, 4 factors with each having 3 levels were selected. Thus, L9 orthogonal array was selected to make the further experiments. The following key process parameters were selected to study their effects on the surface roughness of EN19 steel castings are made by investment casting process. Process parameters and their different levels are shown in Table 1.

Sr. no.	Process Parameters	Level I	Level II	Level III
1.	Mold Pre-heating Temperature (°C)	900	1000	1100
2.	Pouring Temperature (°C)	1450	1550	1650
3.	Sand Type	Zircon	Zircosil	Zircon + Zircosil
4.	No. of Coats	6	8	10

Table 1: Process parameters and their different levels

at low temperatures EN19 steel has good impact properties. It is also suitable for a variety of elevated temperature applications such as gears, bolts, studs and a wide variety of automobile applications where a good quality of high tensile steel grade is suited. The EN 19 steel offers good ductility and shock resisting properties, combined with resistance to wear so this has been chosen for current investigation. The spectroscopic samples were poured to measure the chemical composition of liquid steel. The composition of EN 19 steel used for pouring the castings is shown in Table 2.

Element	Carbon	Silicon	Mn	Cr	Mo	S and P
(%)	0.36-0.44	0.20-0.25	0.7-0.8	0.90-0.95	0.3-0.35	0.035 max

Table 2: Chemical composition of EN 19

The sand types which were selected namely zircon, zircosil and mixture of zircon and zircosil. Zircon sand is fine and gives better surface finish but it is costly. Zircosil sand gives more surface roughness, but it is cheaper than zircon sand. The number of coats decides the strength of mold while pouring. The number of coats selected in the current study are 6, 8 and 10. These four parameters play very important role in determining surface roughness of casting. The composition and properties of sand is given in table no. 3.

Composition	Zircon Sand	Zircosil Sand	Zircon + Zircosil sand
Chemical composition			
ZIRCONIA (ZrO_2)	65.90 %	62.80 %	64.35 %
SILICA (SiO_2)	32.54 %	34.7 %	33.62 %
ALUMINA (Al_2O_3)	1.15 %	0.50 %	0.83 %
TITANIA (TiO_2)	0.27 %	0.10 %	0.19 %
FERROUS OXIDE (Fe_2O_3)	0.04 %	0.07 %	0.05 %
HAFNIUM OXIDE (HfO_2)	--	1.20 %	0.6 %
MISCELLANEOUS	< 0.1 %	< 0.63 %	< 0.36 %
Physical Properties			
BULK DENSITY (uncompacted)	2.80 g/cm3	0.8 g/cm3	1.80 g/cm3
SPECIFIC GRAVITY	4.67 g/cm3	4.60 g/cm3	4.63 g/cm3
MELTING POINT	2300 ºC	2500 ºC	2400 ºC
Grain Fineness Number			
AFS Fineness Number	80	60	70

Table 3: Composition and properties of Sand

The other parameters such as wax pattern, de-waxing temperature, alloy composition and pouring time were kept fixed during the entire investigation.

Mold pre-heat temperatures were decided which were based on part configuration and the alloy to be cast. Common Ranges are: 150 to 540 °C for aluminum alloys, 425 to 870 °C for many copper base alloys, and 870 to 1095 °C for steels and super alloys. The three levels of mold pre-heating temperature were selected in the range of 900°C to 1100°C. Pouring temperature range is selected in between 1450°C to 1650°C. If pouring temperature is below 1400°C the metal tends to solidify in the ladle itself. The mold metal reaction becomes significant above 1700°C, the refractory in ladle may also react with metal and the mold becomes more susceptible to break at higher temperatures. The sand types which were selected namely zircon, zircosil and mixture of zircon and zircosil with different Grain Fineness Number (GFN). The number of coats decides the strength of mold while pouring. The number of coats selected in the current study is 6, 8 and 10. These four parameters play very important role in determining surface roughness of casting. The L9 OA comprising of 4 parameters with each having 3 levels are shown in the Table 4.

Expt. No.	Mold Pre-heating Temperature (ºC)	Pouring Temperature (ºC)	Sand Type	No. of Coats
1	900	1450	Zircon	6
2	900	1550	Zircosil	8
3	900	1650	Zircon + Zircosil	10
4	1000	1450	Zircosil	10
5	1000	1550	Zircon + Zircosil	6
6	1000	1650	Zircon	8
7	1100	1450	Zircon + Zircosil	8
8	1100	1550	Zircon	10
9	1100	1650	Zircosil	6

Table 4: Taguchi L9 standard orthogonal array design matrix

A wax pattern was used for producing shell mold. The shell molds were made by dipping the wax pattern into the primary slurry and keeping dipping and draining drying time 30 and 60 seconds respectively. The coated wax pattern was stuccoes with primary sand by the rainfall sanding method. The pattern was rotated gradually to achieve an even coating of stucco material, which adheres to the surface of the wet slurry. This coat was dried at a temperature of 20°C and 50% relative humidity for 4 hours. After drying, secondary coat was applied by dipping primary coated pattern in fused silica backup slurry and coarse fused silica backup stucco was used. Each secondary coat was dried at a temperature of 20°C and 50% relative humidity and for 4 hours. This secondary coating and stuccoing process is repeated for remaining number of coats. Only first two coats should be of selected sand type and remaining secondary coats to form a self-supporting shell. For dewaxing, the shells were turned in to upside down and placed in a flash firing oven at a temperature 350°C where the wax melts and pours out through the gate and pouring cup. The remaining ceramic shell molds were fired to burn out the last traces of wax, to develop the high temperature bond of the ceramic system and to pre-heat the mold in preparation for casting. The shells (8 to 11 mm thick) were produced for each experimental casting. According to the Taguchi design, molten metal was poured in the self-supported shell molds and 27 castings of the test pattern were produced.

III. Results

As per the design of experiment, each experiment with aforesaid process parameter was performed. Three castings were poured so as to minimize process variation for each of the mold pre-heating temperature, pouring temperature, sand type and the number of coats. Overall 27 castings were poured and quality and surface roughness measurement was performed on each casting. Surface roughness for each trial has been recorded as responses in the respective experiments. The component is fixed to 'V' block and placed on the surface plate. The probe is carefully adjusted in such a position that will touch to the surface to be measured. The roughness is noted in micrometer scale. The surface roughness was measured on the "Mitutoyo" surface finish tester, model SJ – 2000. The set up used for roughness measurement is shown in Fig.2.

Fig. 2: Surface roughness measurement set-up and probe arrangement

A. *Effect of Process Parameter on Surface Roughness of 4 mm Wall Thickness*

In order to see the effect of process parameters on the surface roughness, experiments were conducted using L9 OA. The Roughness value for each trial and S/N ratio against trial numbers are shown in table no. 5.

Expt. No.	Surface Roughness(µM)				S/N ratio	Mean
	1	2	3	Avg.		
1	2.53	2.71	2.67	2.64	-8.4430	2.64333
2	2.94	3.15	2.97	3.02	-9.5905	3.01667
3	3.02	3.04	2.85	2.97	-9.4454	2.96667
4	2.78	2.76	2.82	2.79	-8.9225	2.79333
5	3.22	2.97	3.18	3.12	-9.8831	3.12000
6	3.14	3.07	3.09	3.10	-9.8272	3.10000
7	3.12	3.05	3.07	3.08	-9.7616	3.07667
8	3.23	3.19	2.46	3.20	-10.1120	3.20333
9	3.22	3.97	2.50	3.23	-10.1751	3.22667

Table 5: Roughness value for each trial and S/N ratio against trial numbers

The average values and signal to noise ratios of surface roughness for each of the nine experiments were calculated from the experimental data given in Table 5. The surface roughness found minimum for the process parameters with pre-heating temperature is 900 and pouring temperature is 1450ºC. Surface roughness found minimum for first coats of Zircon sand configuration with total six numbers of coats, along with sealcoat. The surface roughness and average values for each parameter at levels 1, 2 and 3 for S/N data and raw data are displayed in Table no. 6 and Table no. 7 respectively. The graphs of Effects of process parameters on S/N ratio and Effects of process parameters on Surface Roughness is shown in fig. no. 3and fig. no. 4 respectively.

Level	Mold Pre-heating Temperature	Pouring Temperature	Sand Type	Number of Coats
1	-9.160	-9.042	-9.461	-9.500
2	-9.544	-9.862	-9.563	-9.726
3	-10.016	-9.816	-9.697	-9.493
Delta	0.857	0.820	0.236	0.233
Rank	1	2	3	4

Table 6: Response Table for Signal to Noise Ratios (Smaller is better)

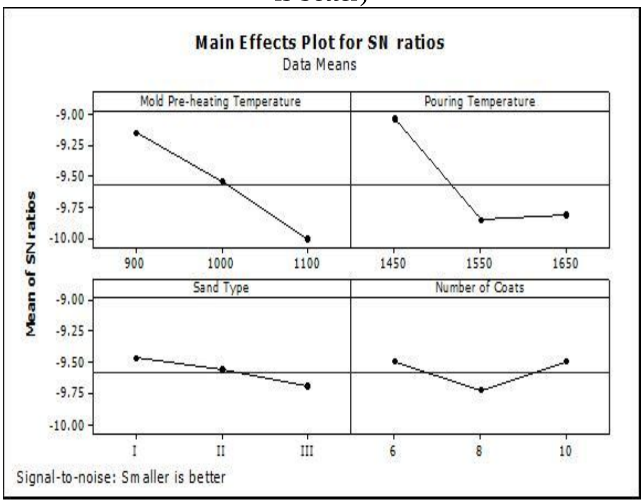

Fig. 3: Effects of process parameters on S/N ratio (main effects)

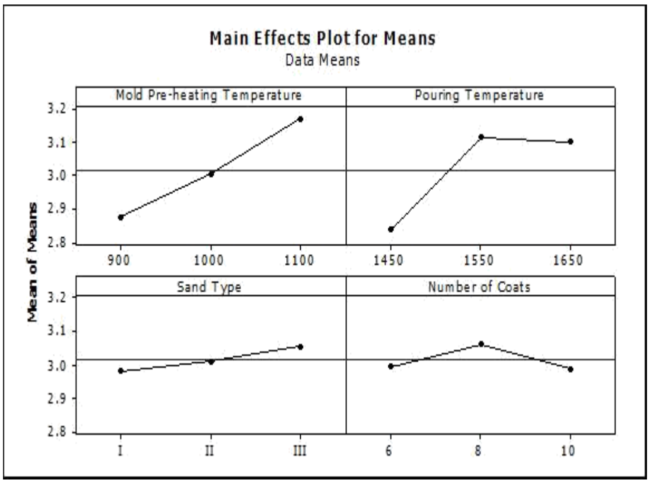

Fig. 4: Effects of process parameters on Surface Roughness (raw data) s

Level	Mold Pre-heating Temperature	Pouring Temperature	Sand Type	Number of Coats
1	2.876	2.838	2.982	2.997
2	3.004	3.113	3.012	3.064
3	3.169	3.098	3.054	2.988
Delta	0.293	0.276	0.072	0.077
Rank	1	2	4	3

Table 7: Response Table for Means

After analyzing the graphs in Fig. 3 and 4, it is observed that the surface roughness increases with increase in pre-heating temperature and pouring temperature. The ANOVA for surface roughness is shown in table no. 8.

Source	DF	Seq SS	Adj SS	Adj MS	% Contribution
Mold Pre-heating Temperature	2	0.129699	0.129699	0.064849	44.43
Pouring Temperature	2	0.143773	0.143773	0.071886	49.25
Sand Type	2	0.007899	0.007899	0.003949	2.71
Number of Coats	2	0.010551	0.010551	0.005275	3.61
Total	8	0.291921	-	-	100

Table 8: ANOVA for surface roughness

To study the significance of the process variables towards surface roughness, analysis of variance (ANOVA) was performed as shown in Table 8. It is observed that mold pre-heating temperature and pouring temperature affect the surface roughness of casting significantly. Table 6 and 7 shows the average of each response characteristic (S/N data), means for each parameter level. The ranks and the delta values are shown in Table 7, indicates the mold pre-heating temperature has the greatest effect on surface roughness compared to other parameters.

IV. Discussion

The EN 19 steel is widely used for applications such as gears, bolts, studs, exhaust manifolds, rocker arms, pump housing, spacers, control arms, steering knuckles, mounts and a wide variety of applications with high tensile strength. These steel have melting temperatures in the range of 1450^{o}C. As mechanical properties are largely depending on the melting temperature range, it is quite difficult to control the surface roughness in case of EN 19 steel.

It is observed that the surface roughness increases with increase in pre-heating temperature and pouring temperature. Increase in pouring temperature causes considerable improvement in casting quality in thin sections. However, the lower pouring temperatures generally give improved soundness in massive or thick casting sections, due to improved temperature gradients sustained during solidification. At higher temperatures, the interactions amongst mold wall sand grains with liquid metal will increase becomes more rugged. Increase in superheat will increase the fluidity of the metal, thus decreasing the surface tension of liquid metal which ultimately spreads in the gaps of facing sand. The mold metal reactions also become more stringent at higher pouring temperatures, resulting traces of sand particles to dissolve in the metal. Due to these reasons the Surface roughness increases with increase in mold Pre-heating temperature and pouring temperature. The surface roughness for zircon sand is very low which can be correlated with the grain fineness number (GFN) for zircon sand, which is 80, whereas GFN for zircosil sand is 60, shown surface roughness comparatively low for zircon + zircosil sand. This variation is due to fineness of sand. With increase in grain fineness number of sand mold, the surface roughness will decrease.

V. Conclusions

The experiments were designed and castings were produced in the jobbing foundry having close control over investment casting processing parameters. The castings were tested for overall quality and surface roughness. The following conclusions are drawn from the study.

1) The pouring temperature, mold pre-heat temperature and sand type significantly affect the surface roughness of investment castings whereas the number of coat parameter is not so significant. Minimum superheat to the pouring temperature improves surface finish.
2) Surface roughness of Investment Castings is found minimum by the use of zircon sand as primary coat. It is observed from the study that, the surface roughness is minimal with 900 ^{o}C Mold pre-heating temperature, 1450 ^{o}C Pouring temperature for zircon sand with 6 coats for EN 19 steel cast by investment casting process.

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